Denoising of Directional Room Impulse Responses Measured with Spherical Microphone Arrays

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Introduction

The use of spherical microphone arrays (SMA) for room acoustic analysis has been widely studied in recent literature (see e.g. [1, 2]). Research has mainly focused on source localization and the extraction of room acoustic parameters from measured directional room impulse responses (DRIR), which are often also referred to as spatial impulse responses (SRIR). In practice, DRIRs are typically corrupted by measurement noise, which limits their use for 3-D reverberation processing and auralization (see e.g. [3, 4]). Due to the exponential energy decay, the noise floor masks especially the late part of the DRIR.

In this paper we present a method for improving the signal-to-noise ratio (SNR) of measured DRIR. This method is based on a statistical space-time-frequency model of the late reverberation decay. It first estimates the spatiotemporal energy decay relief from measured impulse responses and then replaces the corrupted part of the DRIR by a modeled diffuse sound field that preserves the space-time-frequency characteristics of the original field. We applied this method to different DRIR data sets measured in IRCAM's variable acoustics concert hall and briefly discuss the results.

Method

Room impulse responses (RIR) are typically measured with omnidirectional microphones. Traditional RIR noise compensation methods first estimate the time-envelope and noise floor from the Energy Decay Curve (EDC) and then truncate the RIR at the intersection time T_{lim}, i.e. the time where the noise starts masking the exponentially decaying RIR. More advanced methods replace the residual room impulse response tail with an exponentially decaying zero-mean Gaussian noise process and adjust the gain to ensure a smooth transition at T_{lim}. A profound comparison of different RIR noise compensation methods is given in [6].

Jot [5] proposed a time-frequency (TF) extension of the EDC. The Energy Decay Relief (EDR) evaluates the time-reversed energy integration in each frequency band of a Fourier transformed RIR. With reference to the stochastic model of reverberation decays, the TF envelope is assumed to decay exponentially with time for each frequency f_ℓ and is characterized by the initial power spectrum $P(\omega_\ell)$ and the reverberation time $T_R(\omega_\ell)$, where $\omega_\ell = 2\pi f_\ell$. The intersection time $T_{\mathrm{lim}}(\omega_\ell)$ and noise power spectrum $P_n(\omega_\ell)$ are estimated from the EDR with an iterative approach. Then a zero-mean white Gaussian noise process is filtered with the resulting TF envelope to synthesize a noise free late reverberation, which substitutes the room impulse response tail that is corrupted with measurement noise. The results are depicted in Fig. 1.

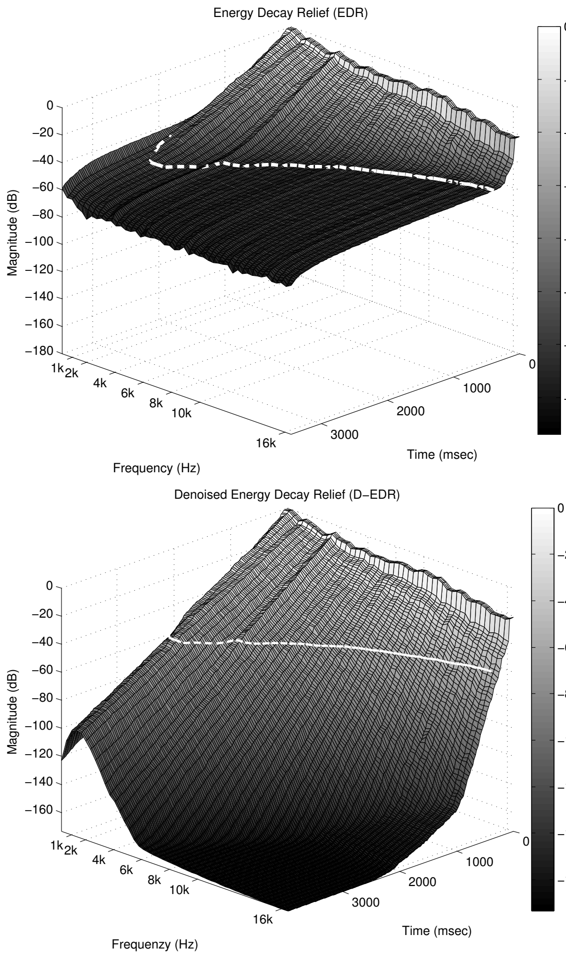

Figure 1: Energy decay relief of a measured DRIR with estimated $T_{\mathrm{lim}}(\omega)$ (white dashed line) before (upper figure) and after noise compensation (lower figure).

We now extend Jot's TF noise compensation method to the space-time-frequency (space-TF) representation of sound fields, by applying the Fourier-Bessel expansion (FBE) to DRIRs obtained from SMA measurements. At a given wave number k, the sound field at position $\mathbf{r} = (r, \theta, \phi)$ due to an incident plane wave from direction

(θ_l, ϕ_l) can be described as (see e.g. [7])

$$p_l(k\mathbf{r}) = \sum_{n=0}^{n=\infty} \sum_{m=-n}^{n} b_n(kr) Y_n^m(\theta, \phi)\, Y_n^{m*}(\theta_l, \phi_l)\,, \quad (1)$$

where the superscript * denotes the complex conjugate, $Y_n^m(\theta, \phi)$ the spherical harmonics of order n and degree m, and $b_n(kr)$ is the holographic function for a sphere with radius $a \le r$. For a sound hard rigid sphere b_n calculates to

$$b_n(kr) = 4\pi i^n \left(j_n(kr) - \frac{j_n'(ka)}{h_n'(ka)} h_n(kr) \right), \quad (2)$$

where j_n and h_n denote the spherical Bessel and Hankel functions, respectively. The design of a robust open SMA is detailed in [8].

With Eq. (1) the model parameters for the reverberation decay can be estimated by applying Jot's iterative method in modal domain (i.e. the wave spectrum). The resulting space-TF envelope describes a filter that transforms a spherically isotropic sound field into a synthetic late reverberation decay to replace the distorted tail of the DRIR. This method not only preserves the TF distribution but also the spatial properties of the late reverberation decay and provides a smooth transition at the intersection time.

The spherically isotropic sound field can be efficiently modeled in the modal domain. It is computed as the superposition of uncorrelated plane waves with unit amplitude and random phase impinging from infinitely many directions on the SMA. This can be approximated by modeling the spherical wave-spectral as mutually independent zero-mean Gaussian noise processes.

Results and Discussion

The proposed method was evaluated with different DRIRs measured in IRCAM's variable acoustics concert hall. Two spherical microphones were used: (a) a 32-channel Eigenmike®, and (b) a rigid-sphere scanning microphone array that provides up to 1261 sampling points on the sphere. Fig. 2 depicts the EDC of the sound field expanded on the position of a microphone on the sphere after noise compensation in modal domain. The influence of noise on the EDC is minimized compared to traditional noise compensation methods; no over-estimation can be observed around the transition time and the dynamic range of the EDC is only limited by the quantization error.

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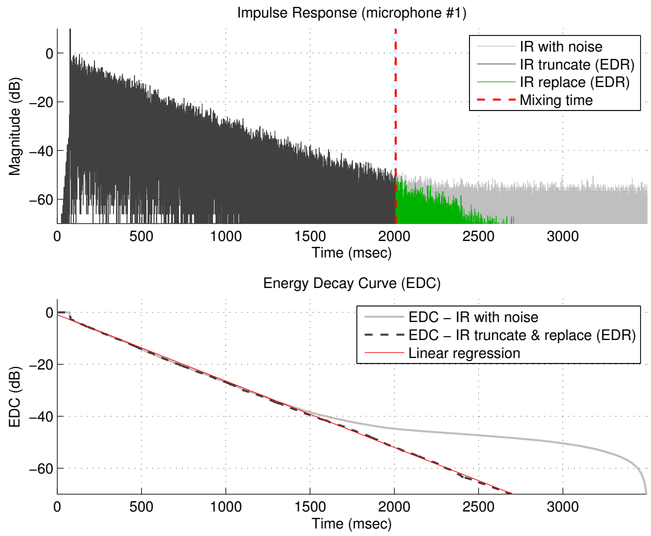

Figure 2: EDC estimated.

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